Stephenson

Investigation of the Coefficient of Cubical Expansion of Steel by Means of the Weight Thermometer

INVESTIGATION OF THE COEFFICIENT OF CUBICAL EXPANSION OF STEEL BY MEANS OF THE WEIGHT THERMOMETER

BY

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THESIS

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY BIRD RICHARD STEPHENSON

ENTITLED INVESTIGATION OF THE COEFFICIENT OF CUBICAL EXPANSION OF STEEL BY MEANS OF THE WEIGHT THERMOMETER

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ARTS

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Recommendation concurred in:*

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*Required for doctor's degree but not for master's.

T A B L E   O F   C O N T E N T S

L I S T O F F I G U R E S

I INTRODUCTION

The specific problem involved in this investigation is the measurement of the coefficients of expansion of four steel cylinders, two and one-half inches long and three fourths of an inch in diameter, carefully turned and ground. The cylinders were cut perpendicular to a radius and at different distances from the center of a railway carwheel. The results of the experiment are to be used in calculating the tensions set up in a car wheel due to unequal expansion when the brakes are applied so as to raise the temperature of the wheel unequal amounts, the rim being the hottest, about 300°C, and the center the coolest, about 20°C. The range of temperature is thus approximately from 20° to 300°C so that means must be secured not only for obtaining this temperature range and for measuring it at any point, but also for measuring the expansions of the steel cylinder.

II THEORY

The coefficient of expansion was determined by means of the weight thermometer. This method was used by Dulong and Petit to determine the expansion of metals and the method is fully discussed in "Theory of Heat" by Preston; "Heat and the Principles of Thermodynamics" by Draper; and in "A Manual of Measurements of Heat" by Guthe, as well as in many other books on heat.

The cylinder to be tested is placed inside a glass bulb as shown in Fig. 1. Mercury fills the remaining volume. On heating the bulb, mercury overflows and affords a measure of the expansion of the solid plus that of the mercury minus that of the glass. If the last two quantities are known, the first is obtainable.

Let V_1 be the volume of the glass bulb at t_1°,

V_2 be the volume of the liquid at t_1°,

and V_3 be the volume of the solid at t_1°.

Then $V_1 = V_2 + V_3$.

If the apparatus is heated to t_2°, the volume becomes

for the vessel, $V_1 \left[1+g(t_2-t_1)\right]$,

for the mercury, $V_2 \left[1+y(t_2-t_1)\right]$,

for the solid, $V_3 \left[1+z(t_2-t_1)\right]$,

where g, y and z are the coefficients of cubical expansion respectively for glass, mercury and the solid.

If V_o is the volume of the mercury that overflows, m, its mass and d, its density, then $V_o = \frac{m}{d}$. Then

$$V_o\left[1+y(t_2-t_1)\right] = V_2\left[1+y(t_2-t_1)\right] + V_3\left[1+z(t_2-t_1)\right] - V_1\left[1+g(t_2-t_1)\right].$$

Solving for

$$z = \frac{V_o - V_2 + V_1 - V_3 + V_o y(t_2-t_1) - V_2 y(t_2-t_1) + V_1 g(t_2-t_1)}{V_3(t_2-t_1)}.$$

$$= \frac{V_o + \left[y(V_o-V_2) + V_1 g\right](t_2-t_1)}{V_3(t_2-t_1)}$$

$$= \frac{V_o}{V_3(t_2-t_1)} - \frac{y(V_2-V_1) - V_1 g}{V_3}.$$

The coefficient of expansion of mercury, y, is calculated from the formula developed by Brock using the results of Regnault as a basis.

$$y = a + bt + ct^2$$

$$= 181{,}792 \times 10^{-6} + .179t \times 10^{-4} + 35{,}116t^2 \times 10^{-12}. \ *$$

From 0° to 100° the average value found by M. Thresen, K. Sheel, and L. Sell is

$$y_{0-100} = 182.45 \times 10^{-6}. \ *$$

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*Winkelmann, "Handbuch der Physik", "Warme", p 87.

The coefficient of expansion of glass, g, was determined experimentally by heating a bulb full of mercury and weighing the overflow. The bulb is first weighed when it is clean and dry, w_0. It is then filled with mercury at room temperature and weighed again, w_1. Then the bulb is heated to t_2°, the overflow being caught and weighed, $(w_2-w_0) = m_2$. Let $w_1-w_0 = m_1$; V_1, the volume at t_1°, and V_2 the volume at t_2°, then

$$V_2 = V_1 \; 1+g(t_2-t_1) \; .$$

For unit mass of the liquid $v_1 = \frac{V_1}{m_1}$ at t_1°, and $v_2 = \frac{V_2}{m_2}$ at t_2°.

Substituting these values in

$$V_2 = V_1 \; 1+y(t_2-t_1) \; ,$$

we get

$$\frac{V_2}{m_2} = \frac{V_1}{V_1} \left[1 + y(t_2-t_1)\right].$$

Hence, solving for g, we get

$$g = \frac{m_2 y}{m_1} - \frac{m_1-m_2}{m_1} \frac{1}{t_2-t_1} \quad .$$

III EXPERIMENTAL

Method of Heating the Bulbs.- The first method tried was to heat the bulb in a simple electric furnace made by winding a heating coil around a sheet of asbestos and then enclosing this in a cylinder of pipe covering. One end was plugged with wet powdered asbestos and then baked hard. After the bulb was enclosed the other end was tightly covered with two pieces of asbestos board. The temperature of this furnace could be raised to any point between room temperature and 400°, and kept fairly constant by supplying a constant current from the storage battery. It was found, however, that when the temperature of the center of the furnace was 300° the temperature near the ends was only 260°. This drop of forty degrees in five centimeters was too great a variation for satisfactory results.

The next furnace tried was a more elaborate one made by Max Kohl, shown at the left in Fig.5. This furnace is about thirty centimeters long with a platinum foil wound around a porcelain cylinder at the center. The cylinder is supported at the ends by porcelain rings so as to leave an air space and these are again supported by a large cylinder of insulating material. Tightly fitting end plugs for the porcelain cylinder were made by fastening together five circular pieces of asbestos board. This furnace was found to have a temperature gradient of about two degrees to the centimeter from the center toward the end. In an attempt to remedy this, an additional plug was made for each end and a small heating coil was inserted between it and the first plug, the terminals of the coil being brought out through small holes in the outside plug. This arrangement reduced the gradient to about one degree per centimeter,

but that was the best that could be obtained because the neck of the bulb projected through the two end plugs. This furnace was also given up as unsatisfactory.

The final form of furnace usedwas an electrically heated oil bath shown in Fig. 5. It consisted essentially of an eight inch porcelain battery jar with a layer of asbestos wound around it and then the heating coil of No.18 Krupp wire wound about this. Another layer of asbestos was wound outside the wire and then the whole arrangement was packed in a metal tub with dry powdered magnesia. Oil known as "superheater" oil was used for the bath. To avoid the smoking and foaming of the oil a practically air tight cover was placed on the jar. A stirrer run by an electric motor maintained the temperature constant throughout. It was possible to maintain the bath at any desired temperature up to 350°C.

Method of Measuring the Temperature.- A copper-constantan thermocouple with a Wolff potentiometer reading to ten millivolts was used at first. The wires were enclosed in glass tubing which was covered with tinfoil and connected to an earthed wire to prevent stray currents. The hot end was placed in a sealed glass tube and the cold end was immersed in oil which was maintained at the temperature of melting ice. The standard cell used was a certified Weston cell and the auxiliary cell was a new storage cell. The couple was calibrated by placing the hot junction successively in steam, freezing tin, and freezing lead. The equation of the couple is calculated to be:

$$E = 3.8t + 0.00308t^2$$

where E is expressed in 0.00001 volts, if the Smithsonian Table values of 232°C and 327.5°C are used for the freezing temperatures

of tin and lead.

This thermocouple was abandoned with the electric furnace because a thermometer reading to 360°C was found more satisfactory with an oil bath. The thermometer was calibrated by the method used for the thermocouple. The curve is shown in Fig. 6. The following tabulation shows the simultaneous reading of the thermometer and thermo-couple when both were heated in the oil bath through a range of temperatures. From the closeness of these readings it is evident that the thermometer gives the temperature as closely as the thermocouple.

Readings on the thermometer	Readings on the thermo-couple
293°.5C	294°C
288.3	288
287.4	287
272.5	272.5
174.8	174.5
172.1	172
142.	142
140.2	140
95.5	96

<u>Method of Filling Bulb</u>.- The bulb was filled by exhausting the air with an air pump and then placing its nose under pure mercury. The mercury was distilled by the method devised by C.T. Knipp.* Air was entrapped in this process. An attempt was made to drive out the entrapped air by boiling the mercury in an electric furnace, but

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*Physik. Zeitschr. XII, p 270, 1911.
Science, 23; March 16, 1906.

the air clung to the sides of the bulb and could not be dislodged. A gas flame was then applied directly to the outside of the bulb. This dislodged the air when there was no cylinder present, but with the cylinder in the bulb the air clung to it and thus could not be boiled out.

The method finally used for filling the bulb with mercury is as follows. The bulb C, Fig. 3, is sealed inside the larger bulb B. A steel wire fastened about C is passed through the bottom tube H to the steel bolt D which can be turned by the handle F. Mercury is poured in at E and as the bulb B is exhausted by Gaede air pumps attached at A the mercury rises, floating C, until the column reaches the barometric height. The pump is kept going and the mercury is boiled for about two hours. The bulb C is then drawn down and allowed to fill partly. It is then released and allowed to float while the mercury is boiled for another hour after which it is drawn down and the whole apparatus allowed to cool with the stop cock at A turned off. This does not remove all the air so the bulb is taken out and boiled with the gas flame until no air can be detected.

<u>Method of Procedure</u>.- Each cylinder was carefully weighed and measured and then enclosed in a glass bulb and the whole weighed again. The bulbs were made from a single long piece of tubing one inch in diameter. After a bulb was filled it was placed in shaved ice with the nose under mercury until it cooled to 0°C. It was then placed in warm water while the overflow was caught in a small glass dish. The bulb was then weighed on a chemical balance sensitive to one milligram, and the small dish with its contents was weighed on a chemical balance sensitive to one tenth milligram. The bulb was then placed in the oil bath with the end of the capillary tube projecting

above the cover so a glass tube could convey the overflow to the small dish off at one side. The bath was now brought to a desired temperature. This was accomplished by using a current-temperature curve, Fig.7, that had been obtained from a previous calibration of the bath. A heavy current from a 125 volt circuit was used until the temperature was within about fifteen degrees of the temperature desired and then constant storage battery current of proper strength was used to complete the heating. After the temperature had remained constant for two or three hours the temperature was read and the dish weighed. Then the temperature was raised about fifty degrees and the process repeated. Five such readings were taken with each bulb over a range from 75°C to 350°C. A sample set of data follows:

Weight of cylinder No.1	122.315 gm.
Length of cylinder No.1	6.331 cm.
Diameter of cylinder No.1	1.858 cm.

Weight of cylinder plus the bulb	149.147 gm.
Weight of cylinder plus the bulb plus mercury	495.11 gm.
Weight of dish and mercury	7.050 gm.

Current	Temperature reading	Weight of dish plus mercury
1.52 amp.	80°C	8.527 gm.
2.5	162.4	12.765
3.02	221.	16.034
3.3	246.6	17.490
3.6	314.	21.345

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IV RESULTS

The results of four trials for the expansion of glass are as follows:

Temperature	Cal. coeff. of expans.	Temperature	Cal. coeff. of expans.
76°.2C	0.262×10^{-4}	74°.5C	0.273×10^{-4}
182	0.275	93.3	0.279
256.6	0.274	114.6	0.278
337.	0.273	154.7	0.274
		198.	0.281
90°.7C	0.277×10^{-10}	93°.6C	0.280×10^{-4}
206.4	0.273	196.4	0.282
266.4	0.275	239.9	0.274
311.	0.268		

From these results, it would appear that the coefficient of expansion of glass is practically constant over the range of temperature used. The variation in the values gives some conception of the accuracy of the method.

Reference tables give values that vary from .000011 to .000024* depending on the composition of the glass. Ordinary German glass tubing has the following values:

temperature	coefficient
10°	.0000255
100°	.0000276
200°	.0000299

The average of these values gives .0000276 which agrees closely with

*Winkelman, Handbuch der Physik, Band III, "Warme", p 63.

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the average obtained in this investigation. The preceding table shows that the coefficient increases in value with the temperature, whereas in this investigation the calculated coefficient either remained practically constant or else decreased slightly with rise in temperature. This indicates that small bubbles of air remained in the mercury and increased the apparent expansion of the mercury, thus giving a calculated coefficient for the glass that appears to be too small. From the average of the results, the following values were used for computations with the later data obtained when the steel cylinders were used.

For temperature near	Coefficient used
100°	$.276 \times 10^{-4}$
150°	.275
200°	.2745
250°	.274
300°	.273

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RESULTS FOR THE EXPANSION OF THE CYLINDERS

Cylinder No.1

Temperature	Computed Coeff. of expansion	Temperature	Computed Coeff. of expansion
78°.5C	0.348×10^{-4}	101°.5C	0.336×10^{-4}
162.	0.350	163.	0.338
223.1	0.351	202.	0.334
250.	0.356	254.7	0.356
320.5	0.369	310.*	0.374

Cylinder No.2

Temperature	Computed Coeff. of expansion	Temperature	Computed Coeff. of expansion
96°.5C	0.388×10^{-4}	96°.5C	0.358×10^{-4}
149.7	0.384	153.5	0.321
199.	0.356	239.6	0.338
244.5	0.355	283.	0.450
272.	0.612	318.7	0.464

Cylinder No.5 / Cylinder No.6

Cylinder No.5 Temperature	Computed Coeff. of expansion	Cylinder No.6 Temperature	Computed Coeff. of expansion
93°.7C	0.341×10^{-4}	79.2	0.490×10^{-4}
149.	0.320	151.3	0.342
197.	0.337	215.	0.334
258.	0.327	261.	0.347
318.	0.445	318.2	0.357

*Temperature uncertain because the stirrer stopped.

The data obtained indicate that the coefficient of expansion for the steel cylinders increases more or less regularly with the temperature. This is in accordance with results found by others. Values* for the coefficient of iron vary from $.33 \times 10^{-4}$ to $.45 \times 10^{-4}$ depending on the temperature and the percentages of added elements. The results obtained in this investigation thus compare favorably with those found by other observers.

It should be noted that the data for the different cylinders show variations that appear anomalous. It seems likely that this irregular variation is due to the presence of bubbles of air either entrapped in the pores and cavities of the cast iron, or else clinging to its exterior.

The following calculations give some estimation of the magnitude of the error that would be caused by entrapped air. Air in the bulb would expand approximately according to the formula $\frac{V}{\theta} = \frac{V_1}{\theta_1}$ since the pressure remains practically constant. From 0°C to 300° a volume of air would expand to $V_1 = \frac{\theta_1}{\theta} V = \frac{573}{273} V = 2.1\ V$; that is, 1 cu.mm. of air in the bulb at 0° would expand to 2.1 cu.mm. at 300°C and would expel approximately 1.1 cu.mm. of mercury. Assuming this volume of air present in the bulb with cylinder No.1, the calculated coefficient would be $.367 \times 10^{-4}$ instead of $.369 \times 10^{-4}$, thus giving an error of approximately .5%. The variation in the data for the other cylinders could be explained in this way.

V CONCLUSIONS

A summary of the investigation shows that temperatures from 0° to 350° may be controlled efficiently by an electrically heated oil

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* Landolt & Börnstein, p 198.

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bath. It was found to be practically impossible to fill a bulb with mercury without having traces of air remain, applications of heat and reduced pressure under varied conditions being unavailable in removing the air.

The experience gained in this investigation would, therefore, indicate that the dilatometer method using mercury as the liquid is capable of only a limited accuracy in determining the coefficient of expansion of steel.

The writer wishes to thank Dr. F.R. Watson, at whose suggestion the problem was undertaken, for his very effective assistance in working out the problem and in writing this thesis. He is also very much indebted to Dr. C.T. Knipp and to Mr. J.B. Hays, Mechanician, for their kindly assistance.

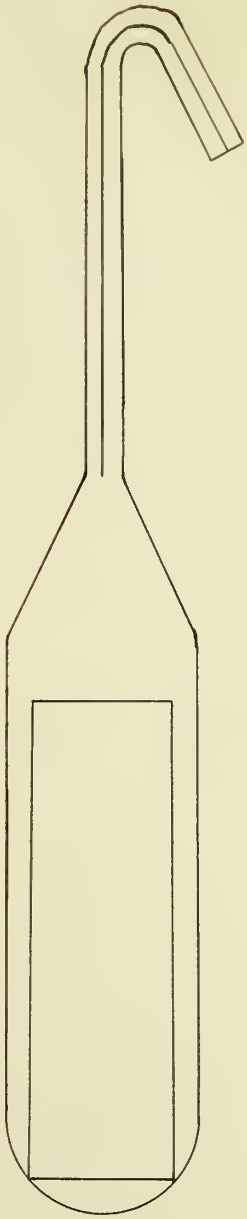


Figure I.

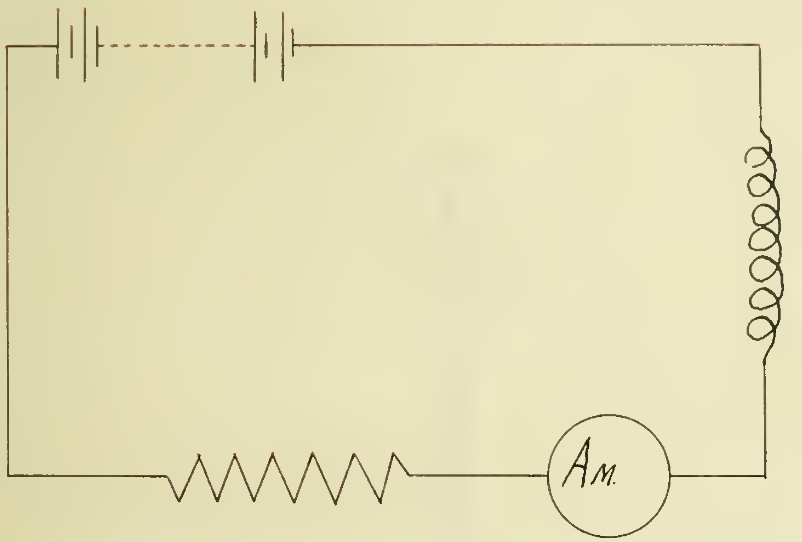


Figure II

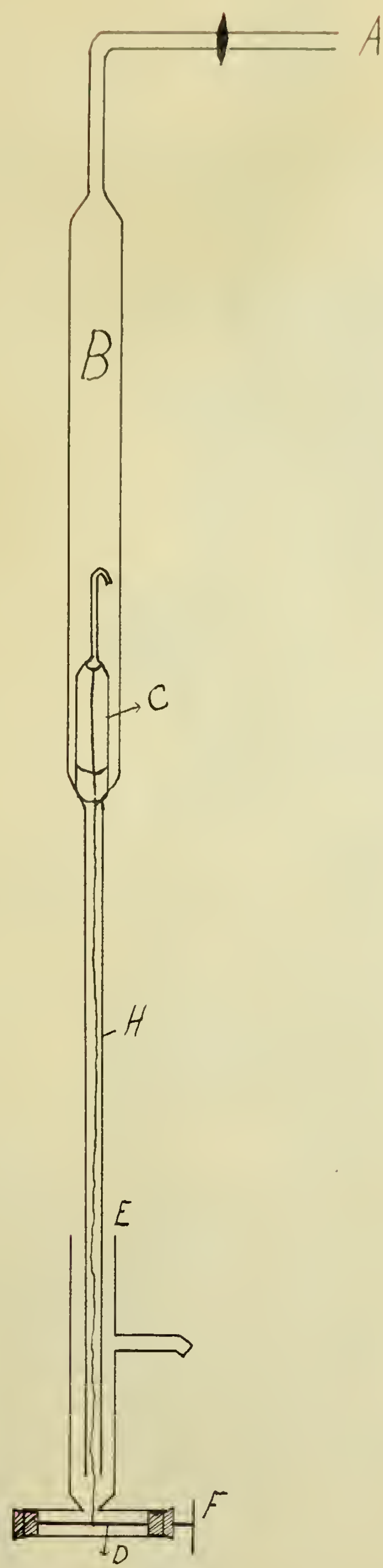


Figure III

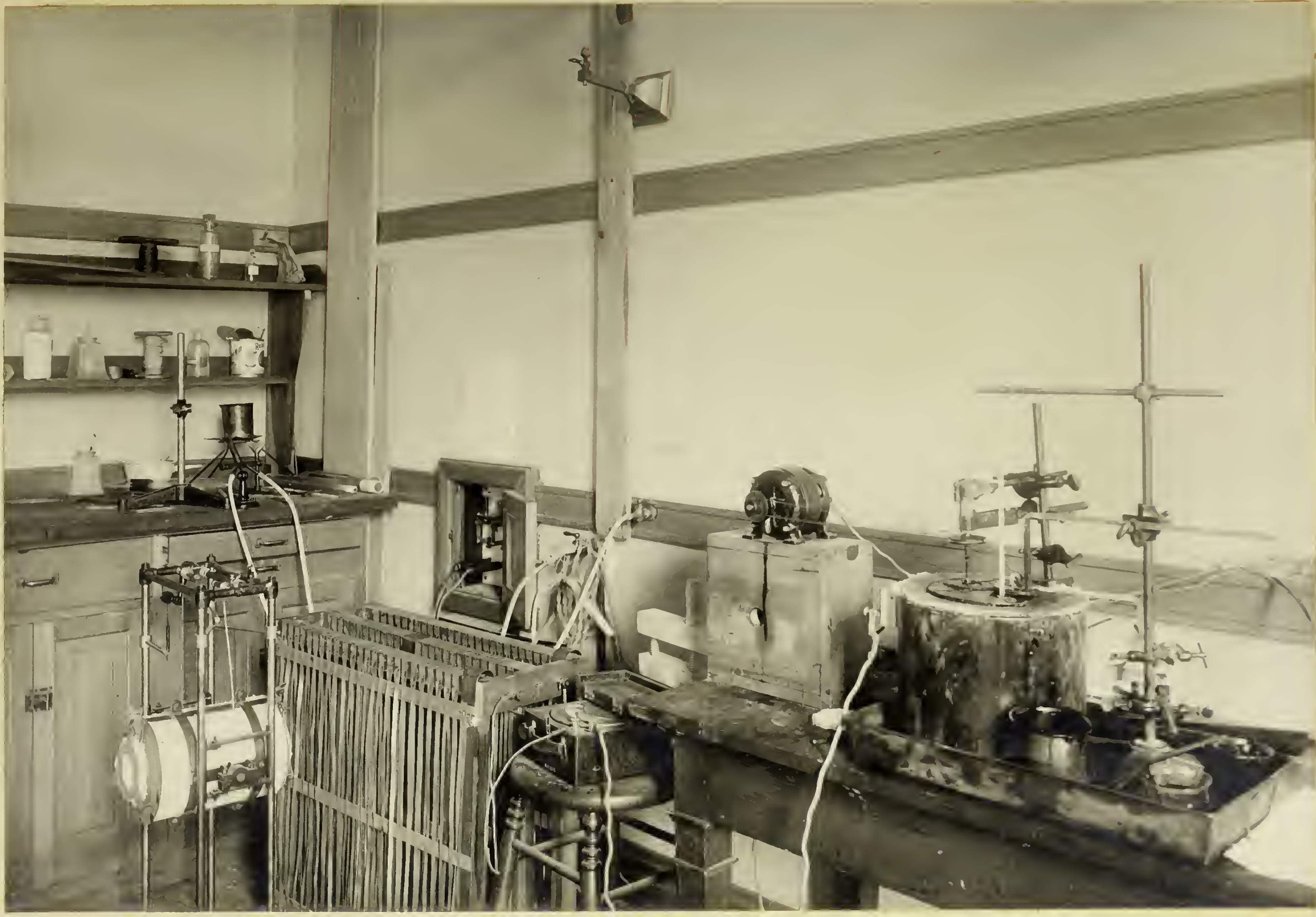
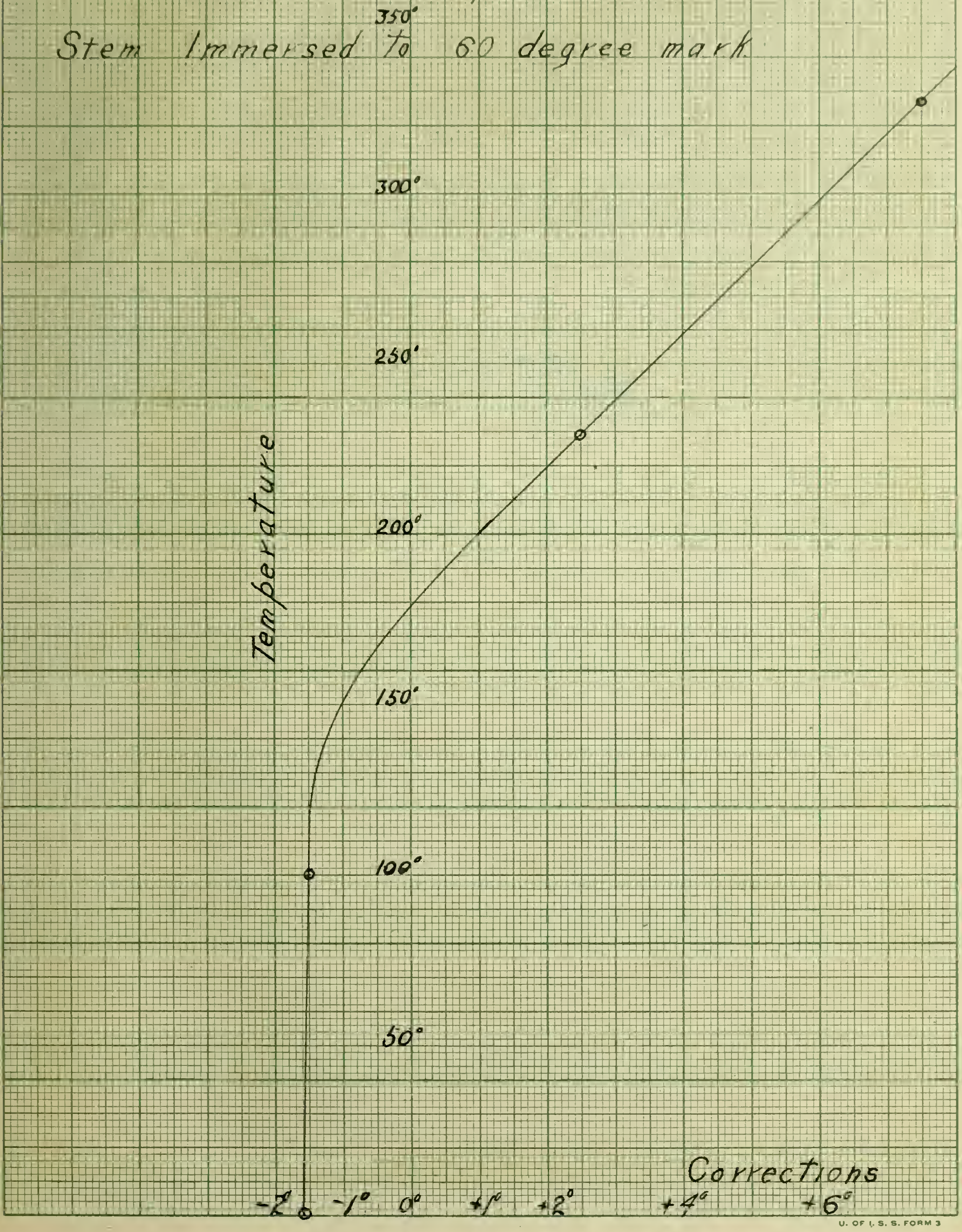
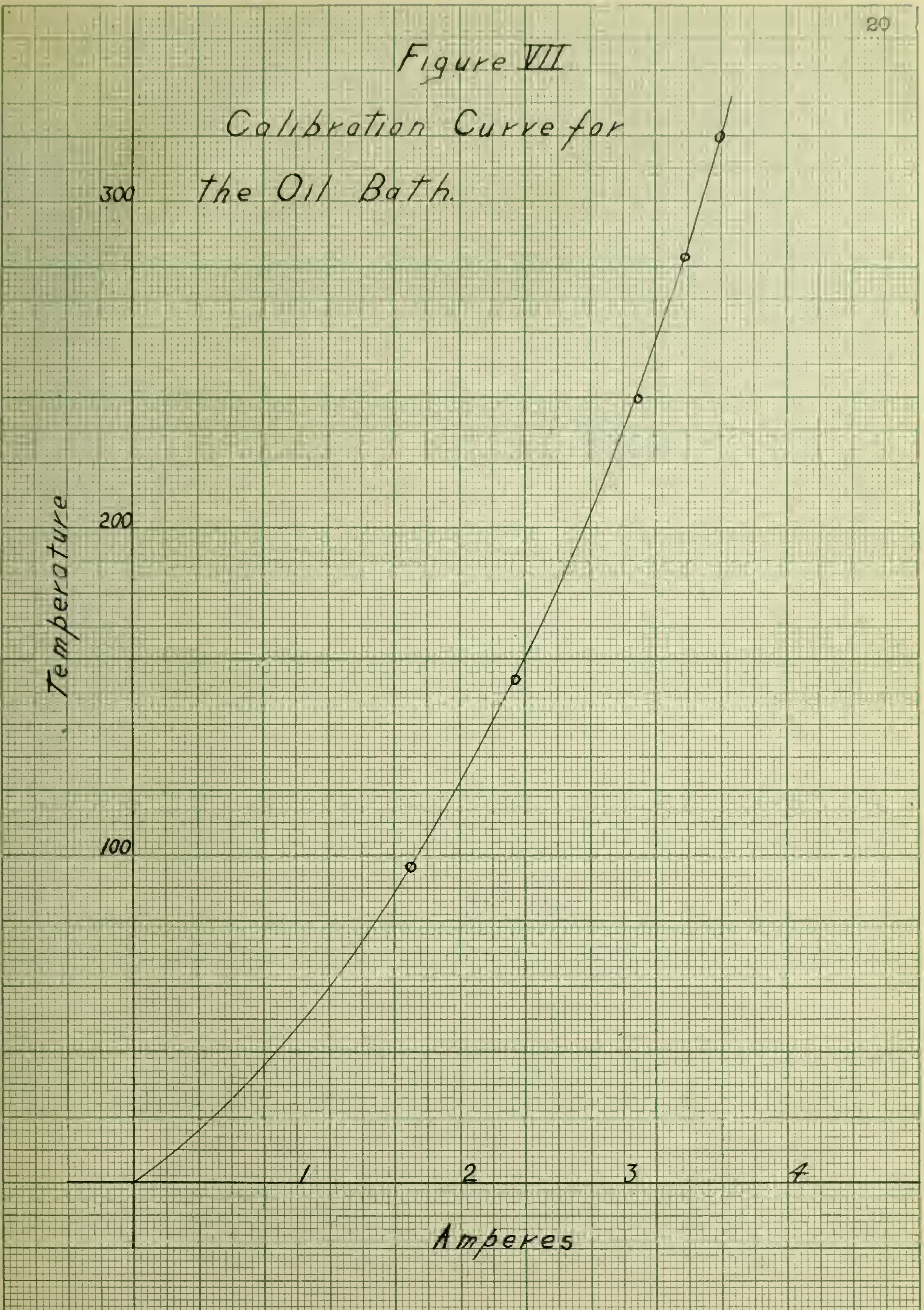


Figure V

Figure VI

Calibration Curve for Thermometer with Stem Immersed to 60 degree mark





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